FUSION: A SAFE, CLEAN AND SUSTAINABLE ENERGY FOR THE FUTURE

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Abstract – Fusion, the nuclear process that powers the sun and other stars, is described and its advantages as a safe, clean and sustainable energy source are pointed out. Research and development activities on magnetic confinement fusion are summarized. The status of the ITER Project, the first experimental fusion reactor carried out in the frame of an international collaboration involving all the G8 members, is described. The planned route towards a commercial fusion power plant is presented.

Keywords – Fusion, clean and safe energy, magnetic confinement, tokamak, ITER

1. INTRODUCTION

The growing demands for energy consumption especially in developing countries, the shrinking availability of classical energy forms and the increasing concerns about the global warming and other damaging effects on the environment due to the burning of fossil fuels have led to energy saving programmes and to the increase of the research and development (R&D) activities on new energy sources.

Fusion is a potential good candidate for supplying base load electricity on a large scale, since its fuel resources are practically unlimited and it is safe and environmentally sound.

This paper describes the fusion energy (section 2), presents the status of the R&D activities on magnetic confinement fusion with particular emphasis on the first experimental fusion reactor (section 3), describes a fusion power plant and reports two possible roadmaps towards the commercial electricity generation from fusion reactions (section 4), underlines the advantages of fusion energy (section 5) and finally presents the conclusions (section 6).

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2. FUSION ENERGY

Fusion is the process that powers the sun and other stars. Energy is released in a fusion reaction when the nuclei of two light elements (hydrogen and its isotopes) fuse together to form heavier ones, with reduction of the total mass of the reagents (Figure 1).

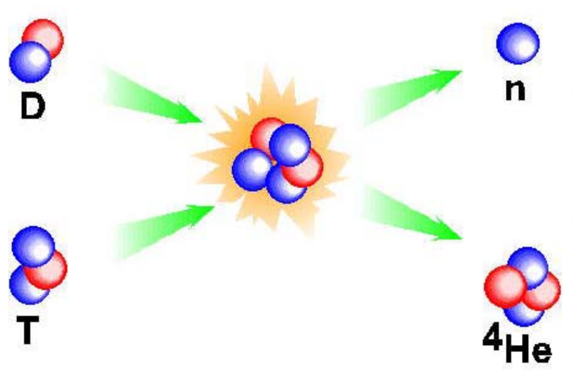

Figure 1 – Deuterium-tritium fusion reaction

Among the fusion reactions [1]

D + T ---- He + n + 17.6 MeV

D + D ---- He + n + 3.27 MeV

D + D ---- T + H + 4.03 MeV

D+ He --- He + H + 18.3 MeV

the most interesting one is that between deuterium and tritium due to the following reasons: (i) this reaction releases 17.6 MeV in the form of kinetic energy of the reaction products: the nucleus of a helium atom (an alpha particle) and a neutron; (ii) the maximum of the cross-section of this reaction occurs at the lowest energy of the hydrogen isotopes (100 keV) (Figure 2); (iii) deuterium can be easily extracted from water (about 20 grams are contained in a cubic meter of water); tritium is a radioactive element, that is virtually non-existent in the Earth, since it has a half-life of only 12.3 years. However it can be bred inside the reactor using the reaction of the fusion neutrons with a blanket containing lithium, an abundant light metal in the nature.

$$Li^6 + n \text{ ---- } T + He^4 + 4.8 \text{ MeV}$$

$$Li^7 + n \text{ ---- } T + He^4 - 2.5 \text{ MeV}$$

Ten grams of deuterium which can be extrated from 500 litres of water and 15 gr of tritium produced from 30 gr the lithium would produce enough fuel for the lifetime electricity needs of a person in an industrialised country.

One gram of deuterium costs about $1 and produces 300 GJ of fusion energy, while 1 kg of lithium costs about $40 and allows generating 3×10^5

GJ of energy. Therefore the costs of the fuels ($0003 per GJ for deuterium and $0.001 per GJ for lithium) are very small compared to the present cost of electricity (about $30 per GJ) [1].

Fusion reactions only occur at high pressures and temperatures (100 million ^{o}C for the D-T reaction) at which the fuels are fully ionised in the fourth state of the matter: the plasma state. A strong extraordinary force is needed to overcome the repulsive force between the nuclei of the two ions. There are three primary ways to bring enough force to bear on atoms to make them fuse [2]:

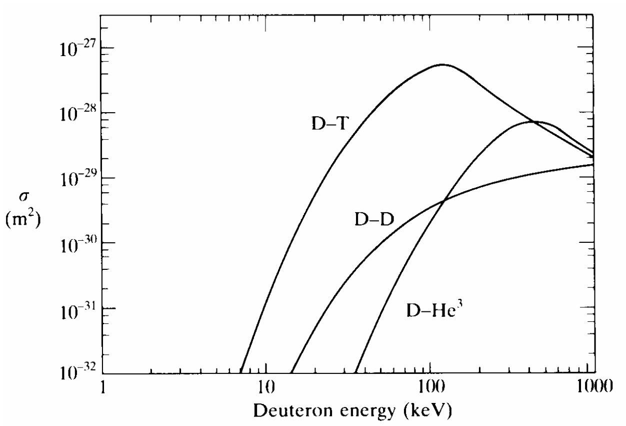

Figure 2 – Cross-sections of the fusion reactions

- *Gravity confinement* – Gravity is the force that gives birth to stars by coalescing, heating and eventually fusing and igniting interstellar matter;
- *Magnetic confinement* consists on the heating on the plasma by Joule effect and by injection of energetic particle beams and radio-frequency waves into the plasma and its thermal isolation from the material walls by strong magnetic fields (slow fusion);
- *Inertial confinement* consists on the compression and heating of solid capsules of the two atoms by laser or high mass ion beams in very short time periods (fast fusion).

3. RESEARCH AND DEVELOPMENT ACTIVITIES ON MAGNETIC CONFINEMENT FUSION

3.1. Introduction

R&D activities on magnetic confinement fusion have been carried out since 1950s all around the world, with particular emphasis on the European

Atomic Energy Community (Euratom)[2], Russia, United States, Japan, China, South Korea, Brazil and India. Two main magnetic configurations have been investigated: tokamak and stellarator. These toroidal configurations are different on the manner how the adequate magnetic field for the plasma stabilization is created: using either external coils plus the plasma current in a tokamak (Figure 3a) or only external non-plane coils in a stellarator (Figure 3b).

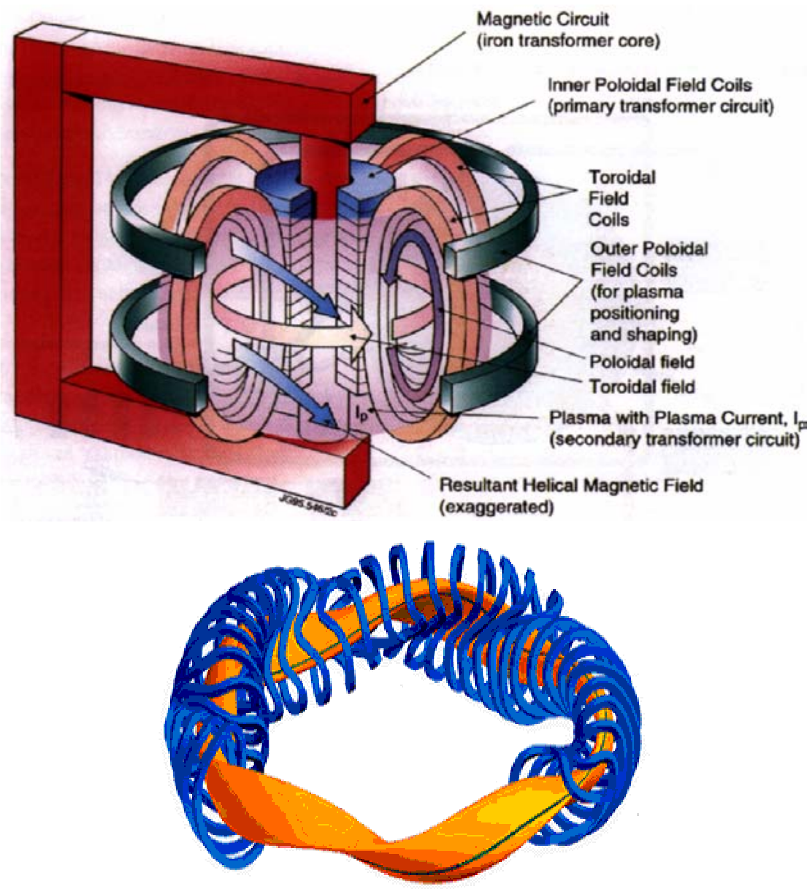

Figure 3 – Schematic drawing of a tokamak and a stellarator

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[2] EURATOM integrates all Member States of the European Union plus Switzerland.

Fusion R&D includes activities on Physics (equilibrium and stability, waves and instabilities, heating and current drive, plasma edge physics), Plasma Engineering (power supplies, high power radio frequency systems, diagnostics, control and data acquisition, plasma control and data handling) and Technologies (vacuum technology, cryogenic technology, superconductivity, plasma facing components, blanket and divertor, materials, fuel cycle, robotics and remote handling).

3.2. Results of the tokamak research

Figure 4 presents the evolution of the triple fusion product (density, temperature and energy confinement time) in magnetic confinement devices.

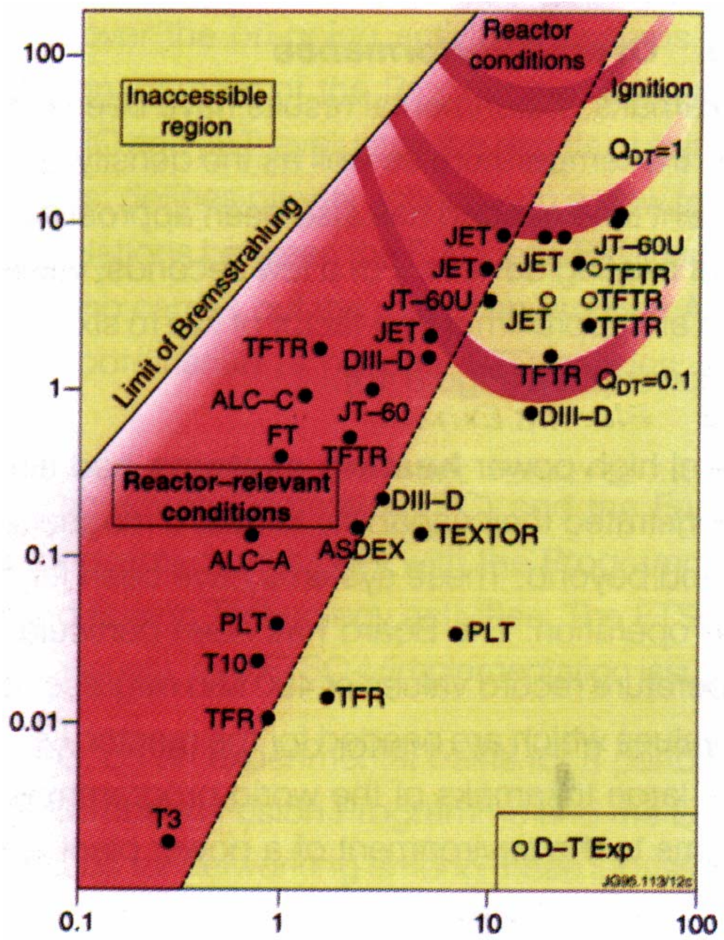

Figure 4 - Evolution of the triple fusion product

The best results have been obtained in tokamaks, particularly in TFTR, JT-60U [3] and JET [4], the single device still in operation with D-T capability. This European tokamak has the world record of fusion power (averaging 1 MW over 2 seconds, using a D-T mixture with 10% of tritium) with a power amplification (Q) (ratio of the fusion power by the total power needed for the operation) of about 0.6. Equivalent break-even (Q=1) has been reached in D-discharges of JT-60U and JET. The highest triple product has been achieved in JT-60U.

Another important JET result was the demonstration of the replacement of a large number of in-vessel components, in an activate environment, by remote handling (Figure 5).

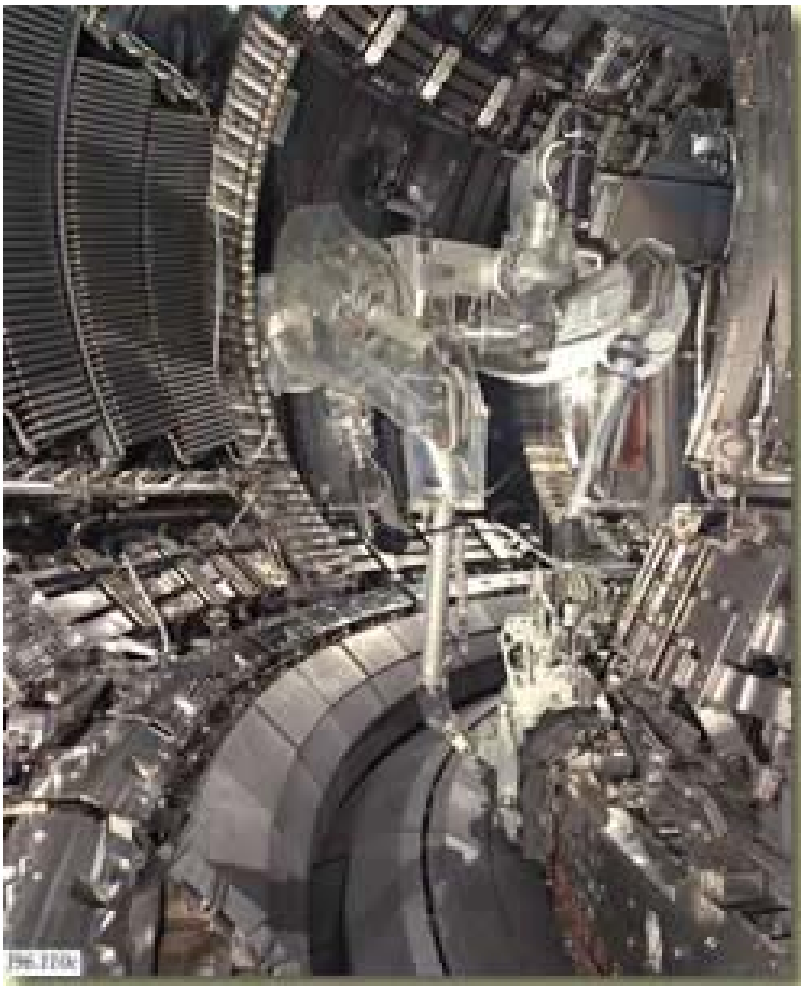

Figure 5 – Manipulator installing the tiles of the JET Mark II divertor

Presently all tokamaks have important programmes on advanced scenario operation aiming at to attain the same plasma performance with smaller geometric parameters of the experimental devices. These investigations need sophisticated diagnostic techniques and efficient real-time control systems.

3.3. ITER Project

The excellent results obtained in tokamaks have led to the choice of this configuration for the design of the first experimental fusion reactor: ITER (Figure 6) [5,6]. The main purpose of this Project is to demonstrate the scientific and technological feasibility of electrical power generation by fusion reactions, including controlled ignition and extended plasma burn, and an assessment of the suitability of candidate materials and technologies for use in fusion reactors. Table 1 compares the main parameters of ITER with those of the tokamaks presently in operation.

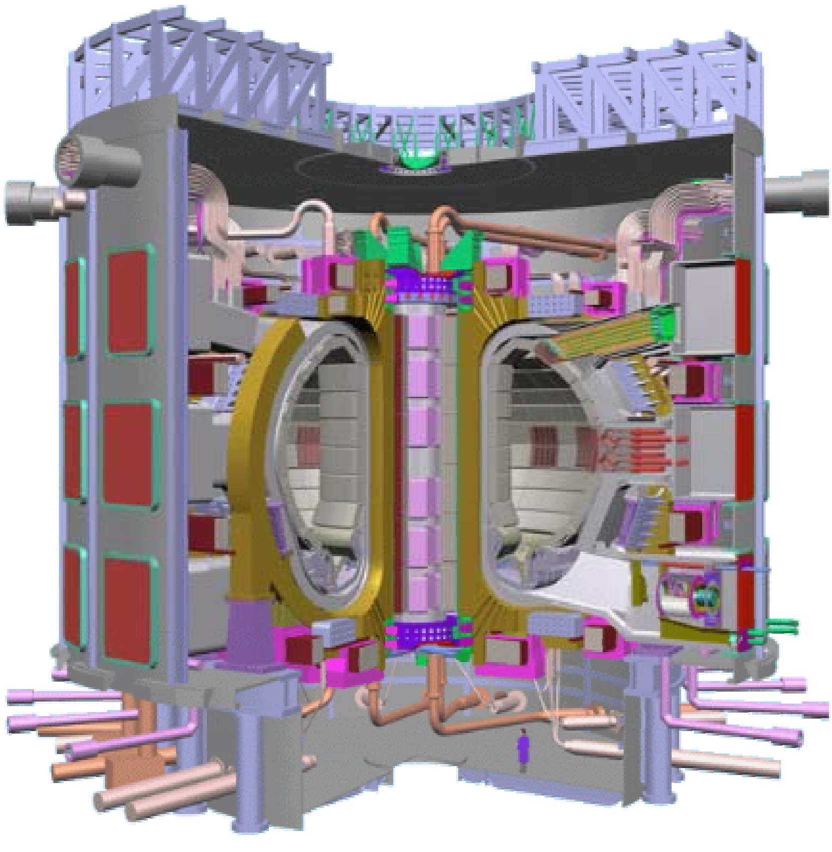

Figure 6 – Schematic drawing of ITER

Table 1 – Main parameters of the largest tokamaks

Parameter	ITER	JET	ASDEX	JT-60U	DIII-D
Major radius (m)	6.2	2.96	1.6	3.4	1.6
Minor radius (m)	2.0	1.2	0.5	1.0	0.56
Toroidal magnetic field (T)	5.3	3.45	3.9	4.2	2.2
Plasma current (MA)	15	4.8	2.0	5.0	3.0
Discharge duration (s)	500	20	10	15	10
Plasma volume (m^3)	850	140	14	100	20
Fusion power (MW)	500	1	-	-	-
Power amplification (Q)	>10	0.6	-	-	-

After two years of Conceptual Design Activities (CDA) and ten years of Engineering and Design Activities (EDA), carried out in the frame of an international collaboration by four Parties (EURATOM, Japan, Russia and United States (until July 2000)), the Final Design Report is ready for implementation, based on well-established physics and proven technologies. Experiments performed in large-size tokamaks have provided a solid physics base for the extrapolation of the results to the ITER scale. A number of high-tech components (such as the superconducting coils, the divertor and the blanket) have been developed by industry and tested. Formal intergovernmental negotiations between EURATOM, Russia, Japan and Canada began in November 2001 aiming at to set-up the Joint Implementing Agreement for the ITER construction, operation and decommissioning. Four candidate sites have been offered and assessed: Vandellos (in Spain), Cadarache (in France), Rokkasho-mura (in Japan) and Clarington (in Canada) (Figure 7). In the meantime and as a result of the growing understanding of the importance of fusion energy, the United States re-joint the Project and other countries have expressed interest to participate (China and South Korea) or to collaborate (Kazakhstan and Brazil) in ITER.

4. FUSION POWER PLANT

Figure 8 shows the schematic drawing of a fusion reactor.

The conventional roadmap towards commercial fusion energy foresees a period of about 50 years after the start of ITER construction and the need of two additional devices: DEMO and PROTO. However and according to experts, this period might be shorten by reducing from two to one the number of experimental machines after ITER. This fast track approach implies the revision of the ITER and PROTO programmes and requires additional resources since more acticities would be carried out in parallel, although the overall funding to reach the final aim could be substantially reduced (Figure 9).

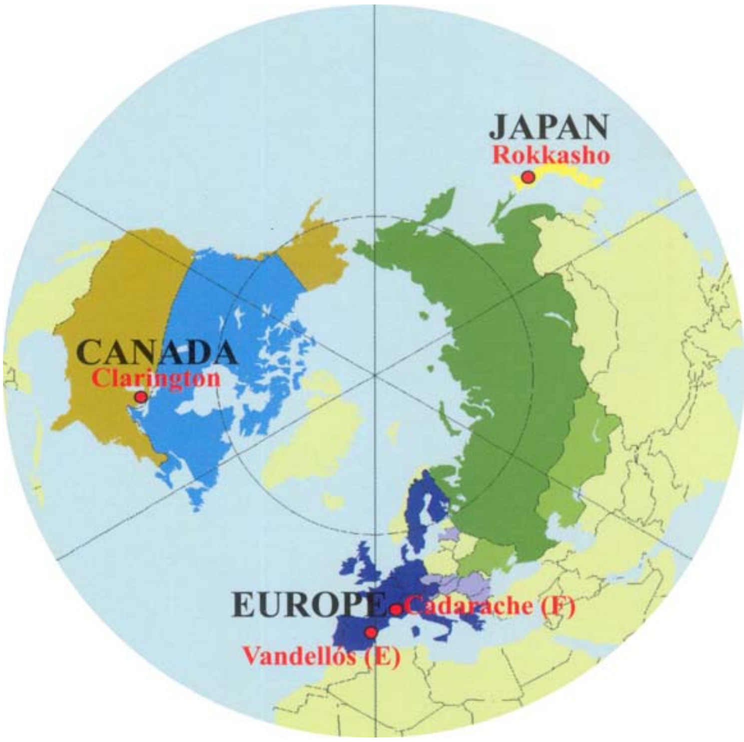

Figure 7 – The candidate sites for ITER construction

5. ADVANTAGES OF FUSION ENERGY

Fusion offers the possibility of an emission-free and reliable long-term energy source with several important advantages [7]:

- The fuels are abundant everywhere for large-scale production. Table 2 presents a summary of the estimated world energy resources, assuming the present world annual primary energy consumption ($3x10^{11}$ GJ;
- The fusion process is very clean since it does not contribute to the greenhouse effect or to the spread of acid rain;
- A fusion power station can be made inherently safe due to two main reasons: (i) a large uncontrolled release of energy would be impossible since the amounts of deuterium and tritium fuels inside the reactor will be very small; and (ii) the fusion reactions can be stopped in a very short time if an accident occurs, since the fuels are introduced inside the reactor while they are burned;

Table 2 – Estimated world energy resources

Resource	Years
Coal	300
Oil	40
Natural gas	50
Uranium 235	30
Uranium 238	30000
Deuterium	3×10^{11}
Lithium – Land	30000
Lithium – Oceans	30×10^{6}

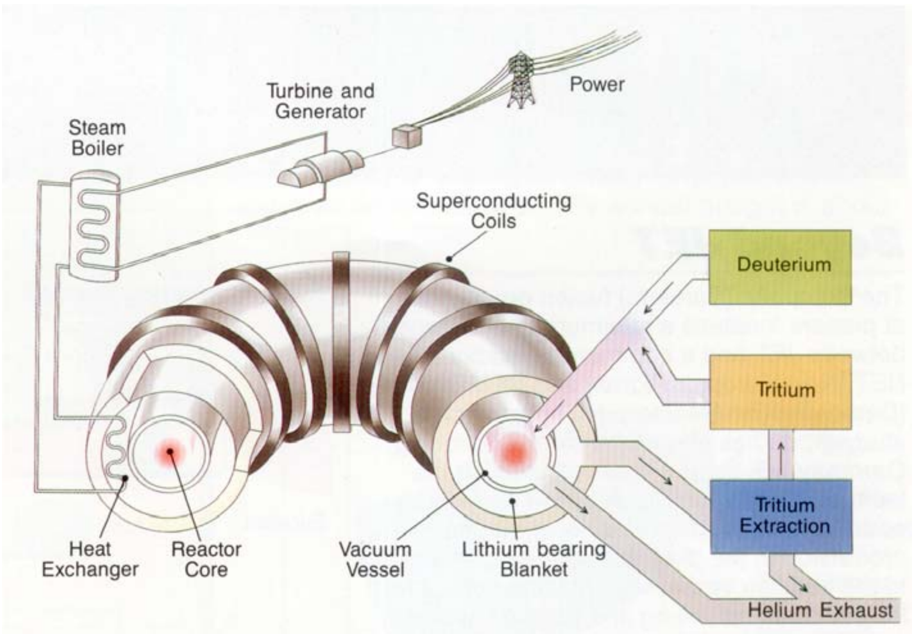

Figure 8 – Schematic drawing of a fusion reactor

- The day-to-day operation of a fusion power station does not require transport of radioactive materials since tritium is produced inside the reactor;
- Waste will not be a long-term burden of the future generation due to the use of low activation materials on the construction of the reactor.

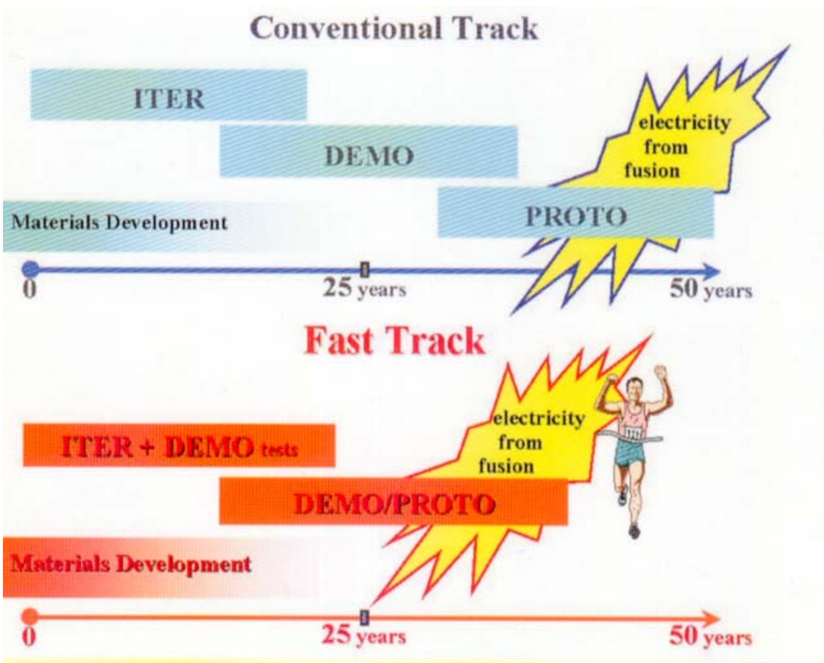

Figure 9 – Roadmaps towards a commercial fusion power plant

6. CONCLUSIONS

Thermonuclear fusion represents potentially a vast environmentally-friendly energy resource for the second half of the twenty-first century. This new energy source is expected to impact the quality of life very strongly, since it will not contribute neither to global warming nor to acid rain.

ITER is an important step towards a commercial fusion power plant. Its design already represents an important scientific and technical achievement, only possible by the intensive cooperation between a large number of physicists and engineers from laboratories, universities and industries of the countries involved in the Project.

Urgent political decisions are needed about both the ITER joint implementation in the frame of a broad international collaboration and the roadmap towards a fusion power plant.

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